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PERFORMANCE OF CELLULAR DS-CDMA SYSTEMS USING DISTRIBUTED ANTENNAS

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ABSTRACT

In this contribution we propose and investigate a high-capacity cellular DS-CDMA wireless communications system, where numerous antennas are distributed in the area covered by the system. The bit error rate (BER) performance of the distributed antenna cellular DS-CDMA system is investigated, when transmission pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading are considered. Our investigation and numerical results suggest that the distributed antenna cellular DS-CDMA system constitutes a high power-efficiency wireless system. For utilizing the same set of system parameters, it is capable of providing an extremely higher capacity, than the cellular DS-CDMA system built on the conventional cellular concepts.

I. INTRODUCTION

Among radio technologies, multiple-input-multiple-output (MIMO) systems using multiple transmit and/or receive antennas have attracted wide research interests in recent years [1]. In this contribution a cellular DS-CDMA system using distributed antennas is proposed and investigated, where a big number of antennas are distributed in the area covered by the system. We consider the DS-CDMA technique, since it has been a typical multiple-access scheme in the second and third generations of wireless communications systems [2], and without any doubt, it will constitute an important candidate in the future generations of wireless communications systems. In the proposed distributed antenna cellular DS-CDMA system, the distributed antennas are connected with a number of signal processing centers, which are referred to as base-stations (BSs), using optical fibers. Note that, the reason for emphasizing optical fible instead of wireless for implementing communications between distributed antennas and BSs is mainly for the sake of saving the highly limited wireless resources. Additionally, we still use the concept of BS, however, it is now rather a signal processing center than a conventional BS. The antennas at the BS of the proposed system are assumed have no priority in comparison with the other distributed antennas. The BS is responsible for the signal processing of the users within the area, which is covered by the distributed antennas connected with this BS.

In this contribution we first describe the distributed antenna cellular DS-CDMA system. Then, the BER performance of the cellular DS-CDMA system using distributed antennas is investigated, when the simplest correlation detector is employed [3]. The BER performance is analyzed and evaluated, when communicating over composite lognormal shadowing slow fading and Nakagami-m fast fading channels associated with transmission pass-loss. Our study shows that, in the distributed antenna cellular DS-CDMA system, the detection is location dependent. It is suggested that the distributed antenna cellular DS-CDMA system constitutes a high power-efficiency wireless system. When using the same set of system parameters, the proposed distributed antenna cellular DS-CDMA system is capable of supporting an extremely higher number of users, than the conventional cellular DS-CDMA systems using centralized BS antennas. The proposed distributed antenna cellular DS-CDMA system is capable of providing a platform for possibly integrating the conventional cellular systems into the future advanced, high-flexibility, ad-hoc and cooperative wireless networks. Furthermore, it may provide an unification platform for finally merging both wireless communications and wired communications into one, so that high-flexibility and high-quality services are available anytime and anywhere.

II. CELLULAR DS-CDMA SYSTEM WITH DISTRIBUTED ANTENNAS

A. System Description

The novel concepts of the proposed cellular DS-CDMA system using distributed antennas can be well-described with the aid of Fig. 1. It is well-known that, in conventional cellular systems, each cell is centered around a BS, which may employ a set of antennas. By contrast, in the proposed distributed antenna aided cellular systems, as shown in Fig. 1, each cell has numerous sets of antennas, which are distributed within the area covered by a cell and are connected to the BS using optical fiber. In the distributed antenna cellular systems of Fig. 1, the antennas near the borders may be connected with two or three BSs, so that soft handoff can be achieved. In more details, as shown in Fig. 1, each of the antennas within the dash-dotted box are, respectively, connected with BS_1 and BS_2 of Cell 1 and Cell 2, while the antennas within the dashed circle at the conner jointing Cells 1, 2 and 3 are all connected with BS_1, BS_2 and BS_3 of these cells.

In the considered distributed antenna system, for the convenience of analysis, we assume that the cells are shaped as hexagons with the common radius of R. We assume that any a pair of adjacent antennas are separated by a distance of r. Hence, each antenna is surrounded by numerous distributed antennas located at the corners of the layered hexagons. Specifically, for the antenna marked as A_3 in Fig. 1, the first layer has six antennas, the second layer has 12 antennas including the antenna located at BS_1, and so on. Note that, the structure of Fig. 1 is sufficiently general for approximately modeling the distributed antenna systems having an arbitrary antenna density. This can be done by appropriately changing the radius value of R in Fig. 1.

In distributed antenna systems as shown in Fig. 1, we assume that the distributed antennas only implement the functions of conveying a signal from radio frequency (RF) to baseband or from baseband to RF, in order to make the computation burden at a distributed antenna as low as possible. The above assumption might be due to the size constraint of the distributed antennas and the constraint arising from some supported signal processing. For example, when advanced multiuser detection (MUD) is employed, information associated with each mobile terminal (MT) and with each antenna should be shared by any individual processor. In this case, using distributed processing in the context of each distributed antenna would require an extremely powerful network for conveying the information timely

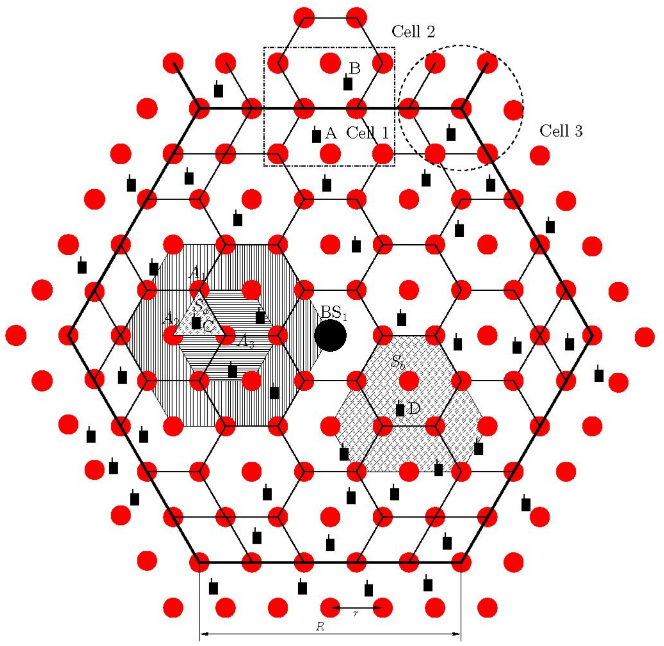

Figure 1: A conceptual cellular DS-CDMA system structure with distributed antennas, where the distributed antennas are connected with one, two or three base-stations (BSs) located at the centers of the cells using optical fiber.

and efficiently, which might not be practical in the near future. Hence, in our distributed antenna system all signals received from the MTs by the distributed antennas are conveyed to the BSs, where the processing is carried out. Simultaneously, all the distributed antennas are also used for transmitting signals from the BSs to the MTs, in order to improve the down-link transmission quality.

In this contribution, specifically, we consider and investigate the distributed antenna systems using DS-CDMA signaling. Hence, when considering conventional binary phase shift keying (BPSK) baseband modulation, the transmitted DS spread spectrum signal, say by the kth MT, can be expressed as

$$s_k(t) = \sqrt{2P} b_k(t) c_k(t) \cos(2\pi f_c t + \phi_k) \quad (1)$$

where P is the user's transmitted power, f_c is the carrier frequency, while ϕ_k denotes the initial phase angle associated with the carrier modulation. The data stream's waveform $b_k(t) = \sum_{n=-\infty}^{\infty} b_k[n] P_{T_b}(t - nT_b)$ consists of a sequence of mutually independent rectangular pulses of duration T_b and of amplitude of +1 or -1, where T_b is the bit duration. Finally, in (1) $c_k(t) = \sum_{j=-\infty}^{\infty} c_{kj} \psi_{T_c}(t - jT_c)$ denotes the signature sequence waveform of the kth user, where c_{kj} assumes values of +1 or -1 with equal probability, while $\psi_{T_c}(t)$ is the chip waveform, which is defined over the interval $[0, T_c)$ and has the property of $\int_0^{T_c} \psi_{T_c}^2(t) dt = T_c$.

Note that, in this contribution we assume that each MT employs only a single antenna, which is sufficient for fulfill our objectives by focusing on the issues of the distributed antenna systems. However, our investigation can be extended to the distributed antenna systems that use multiple MT antennas aided by some advanced transmit and receive schemes [4]. Furthermore, we assume that the distributed antenna cellular DS-CDMA uses no power-control. This is because, as shown in Fig. 1, no matter where a MT is, it communicates with a number of antennas located within its line-of-sight (LoS) area. The signals sampled from the antennas within the LoS area of the considered MT usually fall within the cluster of strongest signal. Consequently, the considered MT will conflict no or light near-far problem.

B. Propagation Channel Modeling

In distributed antenna cellular systems, for any a given MT, there are a number of antennas within the LoS area of the MT. This LoS area is referred to as a virtual cell. The antennas within the virtual cell of a MT are used to communicate between this MT and its BS. Hence, the propagation channel between a MT and any of the antennas within its virtual cell can be well modeled by a composite shadowing-fading model [5], where (slow) shadowing can be described by a lognormal distribution [5], while (fast) fading by a Rician or Nakagami-m distribution [6]. Specifically, in this contribution frequency non-selective Nakagami fading [6] is used to model the fast fading.

Let MT_0 be the reference terminal and assume that the signal transmitted by the reference terminal MT_0 is being detected. The reference terminal MT_0 randomly moves within the triangle area with three antennas at its corners. For example, MT C in Fig. 1 randomly moves within the triangle area S_a. We assume that there are U antennas within the virtual cell of MT_0. Signals collected from these U antennas are processed, in order to detect the information transmitted by MT_0. Let us now analyze the received signal by the uth antenna, which is in the virtual cell of MT_0. Specifically, assuming that $(K+1)$ user signals including that from MT_0 are received by the uth antenna, the received complex low-pass equivalent signal can then be expressed as

$$r_u(t) = \sqrt{2P} h_{0u} b_0(t) c_0(t) + \sum_{k=1}^{K} \sqrt{2P} h_{ku} \times b_k(t - \tau_k) c_k(t - \tau_k) + n_u(t) \quad (2)$$

where $n_u(t)$ is the complex-valued additive white Gaussian noise (AWGN) received by the uth receive antenna, which has zero-mean and a single-sided spectrum density of N_0 per dimension, τ_k represents the channel delay associated with asynchronous transmission and propagation, which is assumed to be uniformly distributed within $[0, T_b)$. Furthermore, in (2) h_{ku} represents the channel gain with respect to MT_k and the uth antenna. The channel gain h_{ku} takes into account both shadowing and fading. Hence, it can be expressed as

$$h_{ku} = \beta_{ku} \alpha_{ku} e^{j\theta_{ku}}, \quad (3)$$

where, without loss of any generality, the initial phase seen in (1) and the phase due to channel have been absorbed into θ_{ku}, and θ_{ku} is assumed to be uniformly distributed in $[0, 2\pi)$. In (3) β_{ku} represents the lognormal shadowing factor, accounting for large scale geographical variation, while α_{ku} represents the fast fading envelope. We assume that the transmission pass-loss is absorbed in the shadowing factor β_{ku}, so that the mean-square value of α_{ku} is unit, i.e., $\Omega = E\left[\alpha_{ku}^2\right] = 1$. Furthermore, we assume that β_{ku} and α_{ku} are mutually independent and both of them are also independent of θ_{ku}.

Since the fast fading α_{ku} is modeled by Nakagami-m distribution, hence, α_{ku}^2 is Gamma distributed with the probability

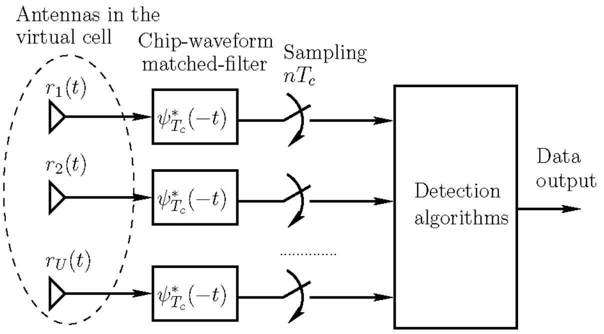

Figure 2: Receiver block diagram for the reference MT in the distributed antenna cellular DS-CDMA system.

density function (PDF) expressed as [6]

$$p_{\alpha^2_{ku}}(y) = \frac{1}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m y^{m-1}\exp\left(-\frac{my}{\Omega}\right),\ y \geq 0 \quad (4)$$

where $\Gamma(\cdot)$ is the Gamma function, and, again, m is a parameter accounting for the fading severity. In (3) β_{ku} represents the shadowing, which can be modeled as lognormal distribution [6]. It can be shown that β^2_{ku} also obeys lognormal distribution having the PDF given by [6]

$$p_{\beta^2_{ku}}(r) = \frac{\xi}{\sqrt{2\pi}\sigma_\beta r}\exp\left[-\frac{(10\log_{10} r - \mu_{ku})^2}{2\sigma^2_\beta}\right],\ r > 0 \quad (5)$$

where $\xi = 10/\ln 10 = 4.3429$, and μ_{ku} (dB) and σ_β (dB) are the mean and standard deviation of $10\log_{10} r$, respectively. Finally, since we assumed that both the fast Nakagami-m fading and the shadowing slow fading are independent random processes, hence the PDF of $|h_{ku}|^2$ is simply the product of (4) and (5).

C. *Representation of The Received Signal*

The receiver structure for detection of the reference signal from MT_0 is shown in Fig.2. As shown in Fig.2 the received signals from the U antennas in the virtual cell of MT_0 are first passed through a bank of filters matched to the chip-waveform pulse of $\psi_{T_c}(t)$. Then, the outputs of the matched-filters are sampled at a rate of $1/T_c$. Hence, in correspondence with each data bit, a total of N samples can be obtained from each antenna, where N represents the number of chips per bit or the spreading factor. Let us consider the detection of the first data bit transmitted by MT_0. Then, the λth sample with respect to the uth antenna can be expressed as

$$y_{\lambda u} = \left(\sqrt{2P/NT_b}\right)^{-1}\int_{\lambda T_c}^{(\lambda+1)T_c} r_u(t)\psi^*_{T_c}(t-\lambda T_c)dt \quad (6)$$

where $\lambda = 0, 1, \ldots, N-1$; $u = 1, 2, \ldots, U$, $\sqrt{2P/NT_b}$ is a normalization factor, and * represents the complex conjugate.

Let

$$\boldsymbol{y}_u = \left[y_{0u}, y_{1u}, \ldots, y_{(N-1)u}\right]^T, \quad (7)$$
$$\boldsymbol{n}_u = \left[n_{0u}, n_{1u}, \ldots, n_{(N-1)u}\right]^T \quad (8)$$

be the N-length observation vector and noise vector corresponding to the uth antenna. According to (6), we can know that the element $n_{\lambda u}$ in $\boldsymbol{n}$ is a complex Gaussian random variable with zero-mean and a variance of $\sigma^2 = N_0/2E_b$ per dimension, where $E_b = PT_b$ represents the energy per bit. Let us assume that $\tau_{ku} = l_{ku}T_c + v_{ku}$, where $l_{ku} \geq 0$ and $0 < v_{ku} < T_c$. Then, upon substituting the received signal in the form of (2) into (6) and expressing in vector and matrix forms, it can be shown that $\boldsymbol{y}_u$ can be expressed as

$$\boldsymbol{y}_u = h_{0u}\boldsymbol{c}_0 b_0[0] + \sum_{k=1}^{K} h_{ku}\boldsymbol{C}_{ku}\boldsymbol{R}_\psi(v_{ku})\boldsymbol{b}_k + \boldsymbol{n}_u \quad (9)$$

where $\boldsymbol{b}_k = [b_k[-1], b_k[0]]^T$ contains the two data bits transmitted by the kth MT within $[0, T_b)$, while the other arguments in (9) are given by

$$\boldsymbol{c}_0 = \frac{1}{\sqrt{N}}\left[c_{00}, c_{01}, \ldots, c_{0(N-1)}\right]^T$$

$$\boldsymbol{C}_{ku} = \frac{1}{\sqrt{N}}\begin{bmatrix} c_{k(N-l_{ku}-1)} & c_{k(N-l_{ku})} & 0 & 0 \\ c_{k(N-l_{ku})} & c_{k(N-l_{ku}+1)} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ c_{k(N-2)} & c_{k(N-1)} & 0 & 0 \\ c_{k(N-1)} & 0 & 0 & c_{k0} \\ 0 & 0 & c_{k0} & c_{k1} \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & c_{k(l_{ku}-2)} & c_{k(l_{ku}-1)} \\ 0 & 0 & c_{k(l_{ku}-1)} & c_{kl_{ku}} \end{bmatrix}$$

$$\boldsymbol{R}_\psi(v_{ku}) = \begin{bmatrix} R_\psi(v_{ku}) & 0 \\ \hat{R}_\psi(v_{ku}) & 0 \\ 0 & R_\psi(v_{ku}) \\ 0 & \hat{R}_\psi(v_{ku}) \end{bmatrix}$$

where $R_\psi(v_{ku})$ and $\hat{R}_\psi(v_{ku})$ are the chip autocorrelation functions, which are defined as $\hat{R}_\psi(s) = \frac{1}{T_c}\int_s^{T_c}\psi_{T_c}(t)\psi_{T_c}(t-s)dt$ and $R_\psi(s) = \hat{R}_\psi(T_c - s)$ for $0 \leq s < T_c$, respectively.

Furthermore, let

$$\boldsymbol{y} = \left[\boldsymbol{y}_1^T, \boldsymbol{y}_2^T, \ldots, \boldsymbol{y}_U^T\right]^T \quad (10)$$

which collects all the samples from the U antennas related to the detection of MT_0. Then, $\boldsymbol{y}$ can be expressed as

$$\boldsymbol{y} = (\boldsymbol{I}_U \otimes \boldsymbol{c}_0)\boldsymbol{h}_0 b_0[0] + \sum_{k=1}^{K}\boldsymbol{C}_k\boldsymbol{R}_{\psi k}\boldsymbol{H}_k\boldsymbol{b}_k + \boldsymbol{n} \quad (11)$$

where

$$\boldsymbol{n} = \left[\boldsymbol{n}_1^T, \boldsymbol{n}_2^T, \ldots, \boldsymbol{n}_U^T\right]^T \quad (12)$$

is an UN-length Gaussian noise vector,which has zero mean and a covariance matrix of $2\sigma^2\boldsymbol{I}_{UN}$, $\otimes$ represents the *Kronecker product* operation, and the other arguments in (11) are given as follows:

$$\boldsymbol{h}_0 = [h_{01}, h_{02}, \ldots, h_{0U}]^T \quad (13)$$
$$\boldsymbol{C}_k = \text{diag}\{\boldsymbol{C}_{k1}, \boldsymbol{C}_{k2}, \ldots, \boldsymbol{C}_{kU}\} \quad (14)$$
$$\boldsymbol{R}_{\psi k} = \text{diag}\{\boldsymbol{R}_\psi(v_{k1}), \boldsymbol{R}_\psi(v_{k2}), \ldots, \boldsymbol{R}_\psi(v_{kU})\} \quad (15)$$
$$\boldsymbol{H}_k = \left[\boldsymbol{H}_{k1}^T \quad \boldsymbol{H}_{k2}^T \quad \ldots \quad \boldsymbol{H}_{kU}^T\right]^T \quad (16)$$

where $\boldsymbol{H}_{ku} = h_{ku}\boldsymbol{I}_2$. Let us now discuss the detection in distributed antenna cellular DS-CDMA systems.

III. LOCATION-AWARE DETECTION AND BIT ERROR RATE

In this section we investigate the location-aware detection in the distributed antenna cellular DS-CDMA systems, where a user signal, say MT_0, is detected based on the observation data sampled from the antennas within the considered user's virtual cell. Specifically, for the correlation detector, the decision variable for detecting $b_0[0]$ transmitted by MT_0 using the maximal ratio combining (MRC) principle [6] can be expressed as

$$Z_0 = \Re\{\mathcal{Z}_0\} = \Re\left\{\boldsymbol{h}_0^H \left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)^T \boldsymbol{y}\right\} \quad (17)$$

where $\Re\{\mathcal{Z}_0\}$ represents the real part of $\mathcal{Z}_0$. Upon substituting (11) into (17), we obtain

$$\mathcal{Z}_0 = \sum_{u=1}^{U} |h_{0u}|^2 b_0[0] + \sum_{k=1}^{K} \boldsymbol{h}_0^H \left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)^T \boldsymbol{C}_k \boldsymbol{R}_{\psi k} \boldsymbol{H}_k \boldsymbol{b}_k + \boldsymbol{h}_0^H \left(\boldsymbol{I}_U \otimes \boldsymbol{c}_0\right)^T \boldsymbol{n} \quad (18)$$

It can be shown that the average BER of MT_0 at the location (x, y) can be computed efficiently using a Gauss-Hermite quadrature integration [7], expressed as

$$P_b(x,y) = \frac{1}{\pi}\int_0^{\pi/2} \prod_{u=1}^{U} \left[\frac{1}{\sqrt{\pi}} \sum_{i=1}^{n} w_i \left(1 + \frac{\Omega}{2\sigma^2 m \sin^2\theta} 10^{(\sqrt{2}\sigma_\beta y_i + \mu_{0u}(x,y))/10}\right)^{-m}\right] d\theta \quad (19)$$

where w_i and y_i are independent of θ, which can be found in [7].

IV. EXAMPLES OF PERFORMANCE RESULTS

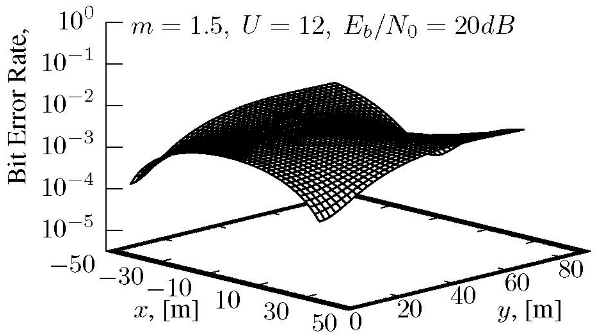

Figure 4: **Single-user bound**: BER versus coordinates (x, y) performance of the distributed antenna cellular DS-CDMA system supporting single user, when the user signal experiences pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

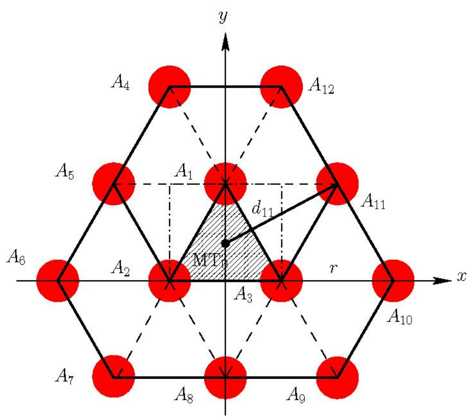

Figure 3: Antennas whose signals may be collected for detection of MT_0, when MT_0 is within the filled area.

In this section we provide a range of results for illustrating the achievable performance of the exemplified distributed antenna cellular DS-CDMA system using a set of specific parameters. Due to the symmetric structure of the distributed antenna system shown in Fig.1, it is sufficient for us to evaluate the BER performance of MT_0, when it moves within the triangular area shown in Fig.3[1], which shows the antennas within the virtual cell of MT_0. Note that the SNR per bit of E_b/N_0 used in the figures of this section represents the average SNR per bit at the MT transmitter location. Conventionally, when transmission pass-loss is not considered or ideal power-control is assumed, the average SNR at the receiver is usually used. Due to the transmission path-loss, it can be readily show that the SNR measured at the transmitter side is significantly higher than that measured at the receiver side for a given value of transmitted power.

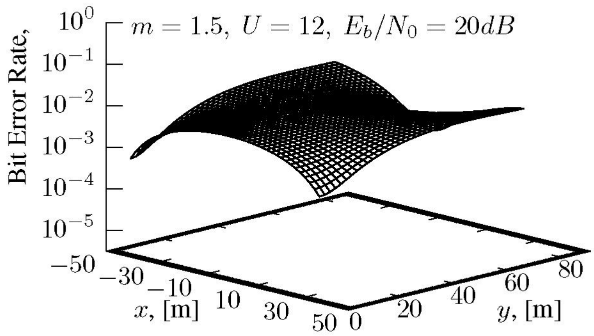

Figure 5: **Correlation**: BER versus coordinates (x, y) performance of the distributed antenna cellular DS-CDMA system supporting K=10000 users, when user signals experience pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

[1] We note that, for the sake of convenience for drawing the figures, in Figs. 4 and 5 the BER within the dash-dotted square was evaluated. However, only the BER corresponding to the triangular area is meaningful.

In Figs. 4 and 5 we evaluated the BER performance of MT_0, when it moved within the triangular area as marked in Fig.3. Specifically, in the context of Fig. 4, we assumed that the distributed antenna cellular DS-CDMA system supported only one user. Hence, the corresponding BER performance represents the single-user BER bound. By contrast, Fig.5 corresponds to the distributed antenna cellular DS-CDMA system supporting $K = 10000$ users per cell.

From the results of Figs. 4 and 5 we can observe that, in distributed antenna cellular DS-CDMA systems, the BER performance does not change significantly, when a MT moves within the system, provided that it is not too close to an antenna. However, when a MT is close to an antenna, the received power by this antenna will dominate the achievable BER performance of the MT and the resultant BER is lower than that achieved, when the MT is far away from all the antennas at certain distances. Comparing the results of Fig. 4 with Fig.5, it can be shown that, in distributed antenna cellular DS-CDMA systems, multiuser interference also degrades the achievable BER performance, in, however, a highly insignificant way upon accounting for $K = 10000$ users supported by the system in Fig.5. The results of Fig.5 imply that the transmission path-loss has significantly mitigated the interference imposed by the MTs having relatively high distances from the antennas considered.

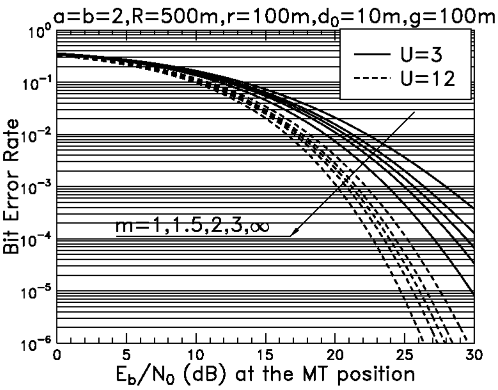

Figure 6: **Single-user bound**: BER versus SNR per bit, E_b/N_0, performance of the distributed antenna cellular DS-CDMA system supporting single user, when the user signal experiences pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

In Fig.6 the single-user BER bound versus SNR per bit of E_b/N_0 performance was evaluated in the context of the distributed antenna cellular DS-CDMA system for $m = 1, 1.5, 2, 3$ and ∞, and for $U = 3$ and $U = 12$. Explicitly, the BER performance improves, when the fast fading becomes less severe, i.e., when the value of the fading parameter m increases. The detection using the signals collected from $U = 12$ antennas outperforms that from $U = 3$ antennas, and the gain for $m = 1$ is about 5dB, while for $m \rightarrow \infty$ is about 3dB, at the BER of 10^{-3}.

In Fig.7 we evaluated the BER with respect to the number of users per cell, K, in the context of the distributed antenna cellular DS-CDMA system using the correlation detection. The results of Fig.7 show that the BER increases, when increasing the number of users supported by the system, or increasing the user density. As shown in Fig.7, for $U = 12$ and for the target

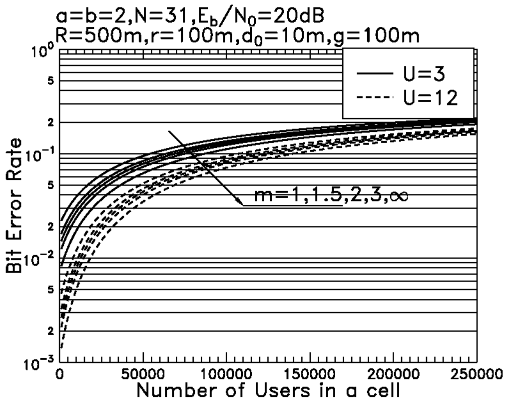

Figure 7: **Correlation**: BER versus the number of users, K, per cell for the distributed antenna cellular DS-CDMA system, when user signals experience pass-loss, lognormal shadowing slow fading and Nakagami-m fast fading.

BER of 10^{-2}, the distributed antenna cellular DS-CDMA system using a spreading factor of $N = 31$ is capable of supporting upto $K = 10000$ to $K = 20000$ users per cell. This high number of users were supported, when employing the simplest correlation detector. Supporting $K = 10000$ to $K = 20000$ users per cell is far beyond the capability of a conventional cellular DS-CDMA system, when it uses the spreading factor of $N = 31$ and employs 91 antennas located at the BS. This is because, in this case, the total number of degrees of freedom available at a BS in the conventional cellular DS-CDMA system is about $31 \times 91 = 2821$, which is impossible to handle $K = 10000$ to $K = 20000$ signals having a similar level of power due to using power control.

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